$A(Q)$ at low Q in ed elastic scattering

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Abstract. The elastic deuteron electromagnetic structure is often considered to be well understood, with excellent descriptions of t_{20} out to 1.7 GeV^2, as well as perhaps 20 - 30% descriptions of the structure function A out to Q^2 of 6 GeV^2, in a number of calculations. The main theoretical difficulty is then having good control on the minimum of the structure function B, which theoretically results from delicate cancellations and experimentally is not well determined.

In this proposal we point out that, at low momentum transfer, theoretical precision of a few percent is possible, but an ≈8% discrepancy between the high (<2%) precision Mainz and Saclay data sets for Q about 0.2 - 0.4 GeV makes the comparison between experiment and theory difficult. We argue that the best conventional relativistic theories suggest the Mainz data are correct, but the overlap of higher Q Saclay data with other data sets suggests that the Saclay data are correct. Our analysis of both Mainz and Saclay data sets suggests potential problems, from the overlap of points within each experiment. Recent chiral perturbation theory calculations, with no adjustable parameters, reproduce the Saclay data; higher order corrections have not been calculated and would be needed if the Mainz data are correct. Finally, extraction of the neutron charge form factor from deuteron elastic scattering is both model dependent and very sensitive to these small cross section differences.

Thus, we request five days of beam time to measure the ed elastic scattering $A(Q)$ structure function at low Q, to resolve this important discrepancy. A ≈2% absolute $d(e,e')d$ cross section measurement is feasible in Hall A, with some improvements in systematics. Relative cross sections can be measured significantly better, and will ensure that the proposed measurements will be definitive.

I INTRODUCTION

In the past decade, our understanding of the elastic deuteron structure has advanced due both to a wide variety of theoretical work and to a few key experiments. The foundation of microscopic calculations is nucleon-nucleon scattering; modern potentials derived during the 1990s have a nearly ideal description of the nucleon-nucleon force, with a reduced χ^2 of about 1 for a pruned nucleon-nucleon data base [1]. The properties of the deuteron can then be predicted in a variety of approaches. The deuteron structure has recently been calculated in several different formulations, as we shall show below in Section II A, but not all of these calculations are at the same level of theoretical maturity.

Much of the effort recently has focussed on large momentum transfer scattering. The key recent experiments, all performed at Jefferson Lab, include the measurement of the recoil tensor polarization t_{20} to four momentum transfers of $Q^2 = 1.7$ GeV^2 [2] and the structure function A to $Q^2 = 6.0$ GeV^2 [3]. Comparison of these results to theory has shown that the deuteron structure can be explained with conventional hadronic theories; simple quark models do not predict the data well.

Figure 1 provides a summary of this conventional view of the deuteron structure. There are a number of theoretical calculations, to be described later in Section II A 3, which provide an excellent description of t_{20}. The structure function A can be described well, to 20 - 30%, as it falls about eight orders of magnitude. Differences of $\approx$10%, which exist between the Jefferson Lab Hall A [3] and Hall C [4] data, are nearly invisible in this plot, and the slight systematic differences between some of the t_{20} data sets also do not seem to be very important. (Complete sets of references to the data, and further discussion on these issues, can be found in recent fits [5] and reviews by Garçon and Van Orden [6], by Sick [7], and by Gilman and Gross [8].) The main theoretical difficulty is then having good control on the minimum of the structure function B, which theoretically results from delicate cancellations and experimentally is not well determined.

In this proposal, we focus on a low momentum transfer measurement of the structure function A. For low energy and momentum transfers, there has been enormous progress in the last few years on a description of the nucleon-nucleon system and the deuteron using both pionless effective field theory (EFT) and chiral perturbation theory (χPT); these approaches may be considered to be firmly tied to quantum chromodynamics (QCD). Quantitative agreement between the theory and data is now possible. But the $\approx$8% discrepancy between the high (<2%) precision Mainz [9] and Saclay [10] data sets for Q about 0.2 - 0.4 GeV [1] makes the comparison between experiment and theory difficult. This difference may appear small and unimportant, but, to put it in perspective, a 10% uncertainty in A in a region in which its magnitude is 10^{-1} - 10^{-2} is much greater than a 100% uncertainty in B in a region in which its magnitude is 10^{-8}.

Furthermore, we argue that the best conventional theories suggest the Mainz

1) We use $Q = \sqrt{Q^2}$ throughout this proposal; $Q \neq |\vec{q}|$.

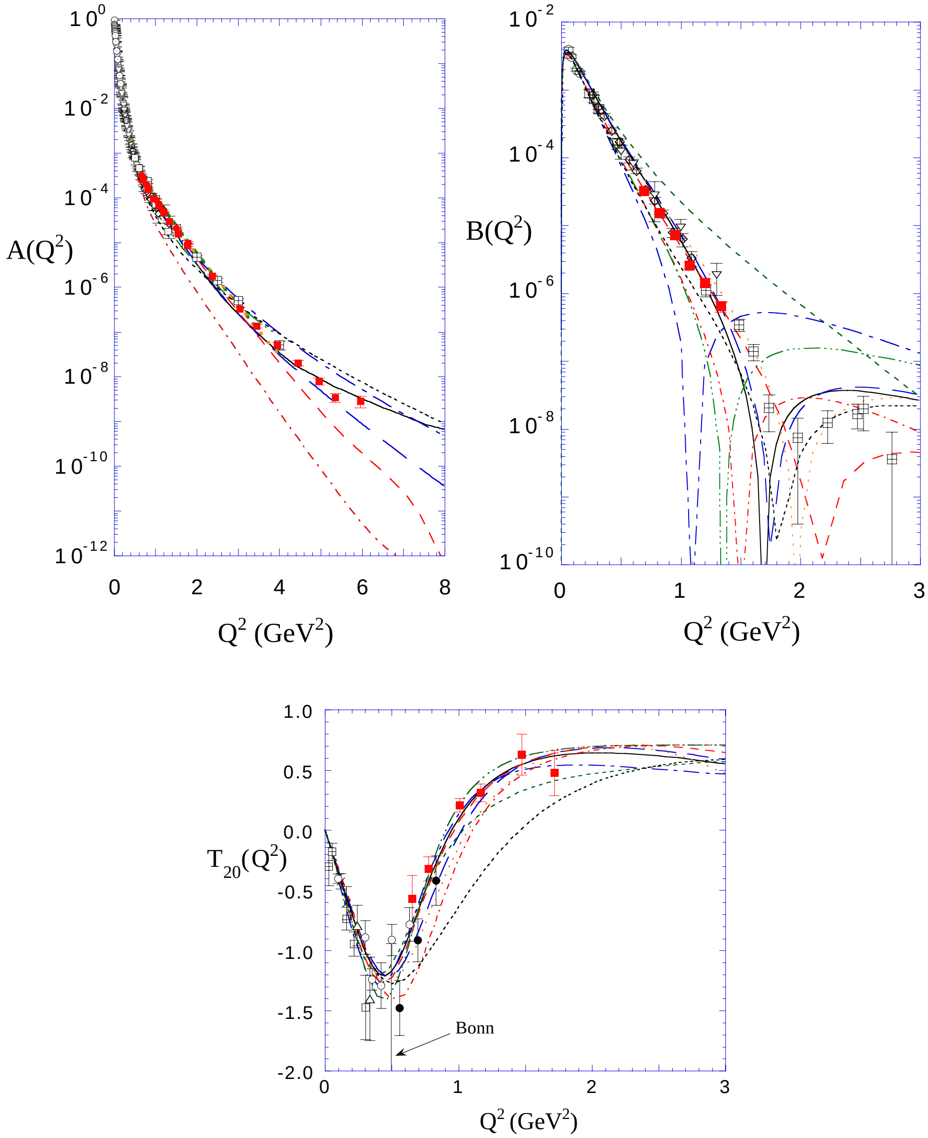

FIGURE 1. Experimental data for A, B, and t_{20} compared to eight calculations. The calculations, in order of the Q^2 of their mimima in B, are: CK (long dot-dashed line), PWM (dashed double-dotted line), AKP (short dot-dashed line), VOG full calculation (solid line), VOG in RIA (long dashed line), LPS (dotted line), DB (widely spaced dotted line), FSR (medium dashed line), and ARW (short dashed line).

data are more nearly correct than are the Saclay data. If indeed they are correct, a few of the theories provide a reasonable description of *all* of the deuteron elastic scattering data, while if the Saclay data are more nearly correct, *no* conventional theory provides a reasonable description of all of the data. However, the overlap of higher Q Saclay data with other higher Q data sets suggests that the Saclay data are correct.

Thus, with an increasing variety of theoretical approaches, and with the improved theoratical precision of recent years, the discrepancy between the Saclay and Mainz data sets has become an important issue that needs to be resolved. Experimentally, data rates are high, and the experiment can be quite easily done in minimal time in Hall A; our beam time request is for five days. The main experimental issues include maintaining a good control of systematics, and being able to prove the correctness of the results, as they are likely to disagree with one of the existing high precision data sets.

II DETAILED MOTIVATION

In the one-photon exchange approximation [12] elastic scattering from the spin-1 deuteron is fully described by two structure functions involving three deuteron form factors [13–15]. The cross section is given by

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{NS} \Big[A(Q) + B(Q)\tan^2(\theta/2)\Big] \equiv \left.\frac{d\sigma}{d\Omega}\right|_{NS} S_d(Q,\theta) \tag{1}$$

where

$$\left.\frac{d\sigma}{d\Omega}\right|_{NS} = \frac{\alpha^2 E' \cos^2(\theta/2)}{4E^3 \sin^4(\theta/2)} = \sigma_M \frac{E'}{E} = \sigma_M \left(1 + \frac{2E}{m_d}\sin^2 \tfrac{1}{2}\theta\right)^{-1} \tag{2}$$

is the cross section for scattering from a particle without internal structure (σ_M is the Mott cross section), and θ, E, E', and $d\Omega$ are the electron scattering angle, the incident and final electron energies, and the solid angle of the scattered electron, all in the lab system. The structure functions $A(Q)$ and $B(Q)$ depend on the three electromagnetic form factors as

$$\begin{aligned} A(Q) &= G_C^2(Q) + \frac{8}{9}\eta^2 G_Q^2(Q) + \frac{2}{3}\eta G_M^2(Q) \\ B(Q) &= \frac{4}{3}\eta(1+\eta)G_M^2(Q)\,, \end{aligned} \tag{3}$$

with $\eta = Q^2/4m_d^2$. In many kinematics the contribution of $B(Q)$ to the cross section is small and $A(Q)$ can be reliably extracted from the cross section without a Rosenbluth separation. In the kinematics of this proposal, $B(Q)$ generally contributes $< 1\%$ to the cross section.

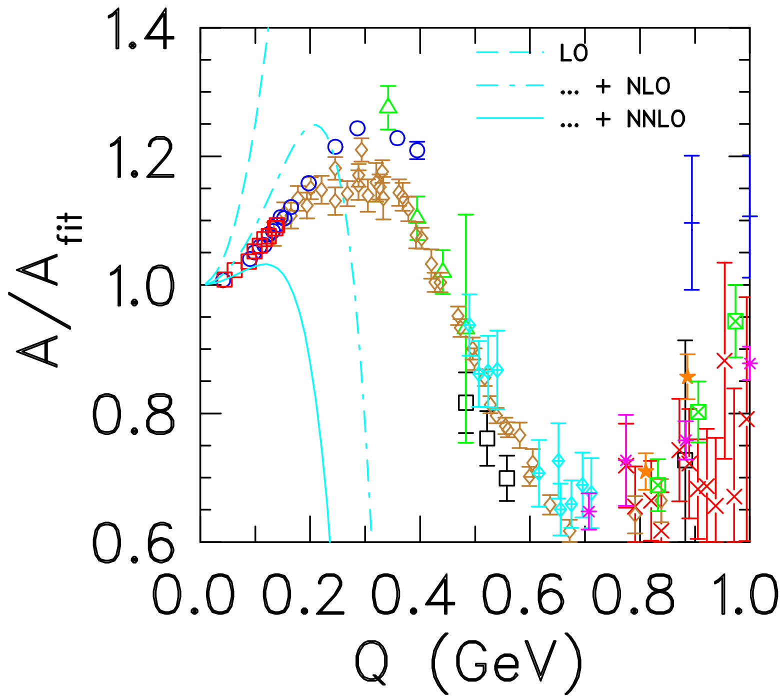

FIGURE 2. The data for A at low and moderate Q, divided by a fit function described in the text. The data sets are described in Table 1. The pionless EFT calculations are described in Section II A 1.

A selection of the world data set for $A(Q)$ is shown in Figure 2 and summarized in Table 1. (The same symbols are not used in all of the figures.) More complete listings can be found in [5], or in recent reviews by Garçon and Van Orden [6], by Sick [7], or by Gilman and Gross [8]. We use a "fit" function with the data to take out much of the momentum dependence of the data, so that differences not visible on a several decade semilog plot can be seen. The fit employs parameterizations of each of the three form factors that have the correct $Q = 0$ limit, and asymptotic fall offs about as would be expected from a simple potential model. The "fit" structure functions are then generated from the "fit" form factors in the usual way, following Equation 3. We do not claim any theoretical significance for these "fit" functions; they are used simply to allow linear plots that emphasize differences.

Of particular interest to this proposal are the high precision lower Q measurements from Monterey [11], Mainz [9], and Saclay [10]. The main point from Figure 2 is that in the region of $Q \approx 0.2$ - 0.4 GeV, the Mainz (and lowest Orsay) data are about 10% larger than are the Saclay data, a very significant difference given the $\approx$1 - 2% claimed uncertainties of the experiments. The difference between the data sets is also of significance to the theoretical interpretaton. In Section II A below, we will review the theoretical calculations and demonstrate the importance of resolving the discrepancy. In Section II C, we will return to the data and examine it in more detail; we shall show below that there is some internal evidence in both of

TABLE 1. Some measurements of A.

Experiment	Q (GeV)	Symbol	# of points	Year and Reference
Monterey	0.04 - 0.14	□	9	1973 [11]
Mainz	0.04 - 0.39	○	16	1981 [9]
Saclay ALS	0.13 - 0.84	◇	43	1990 [10]
Orsay	0.34 - 0.48	△	4	1966 [17]
Stanford	0.48 - 0.88	□	5	1965 [16]
DESY	0.49 - 0.71	◇	10	1971 [19]
CEA	0.76 - 1.15	×	18	1969 [18]
JLab Hall C	0.81 - 1.34	⋆	6	1999 [4]
JLab Hall A	0.83 - 2.44	□	16	1999 [3]
SLAC E101	0.89 - 2.00	+	8	1975 [20]

the data sets of problems.

A *Theoretical Calculations*

Because a number of reviews have recently appeared covering deuteron elastic scattering [6–8], we will in this proposal focus on the results of the calculations at low Q; we will not discuss in detail the theoretical input and calculation procedures, which can be found in the reviews and in the original articles.

1 Low momentum transfer calculations, related to QCD

Figure 2 showed pionless EFT calculations, from the recent work of Phillips, Rupak, and Savage [24] (PRS), applied to $A(Q)$. The NNLO calculation gives factor of two agreement with the data for momentum transfer up to $Q \approx 0.25$ GeV, near the lower limit of the kinematics of this proposal. It is now known that there are difficulties in early approaches treating the tensor part of the one pion exchange interaction perturbatively, and PRS represents the most recent work on improving the convergence of pionless EFT. PRS find that the low Q deuteron properties are largely determined by the asymptotic S wave normalization, akin to the much older effective range theory of Bethe [25]. They also suggest that problems with the quadrupole moment in conventional theories arise from a missing piece of physics, a four-nucleon-one-photon contact term, not determined by NN scattering, that can be used to fit the quadrupole moment in EFT. Note that the $A(Q)$ in the Q range of this proposal is determined almost solely by the deuteron charge form factor, to within a few percent. A higher order calculation might extend agreement into the Q range of this proposal, but it will involve the determination of additional constants from the data, and thus may lack predictive power.

Several χ perturbation theory (χPT) calculations have also appeared. Figure 3 compares the $A(Q)$ data to a recent calculation [26] using χPT wave functions for the deuteron, with the χPT current operator at NNLO. Once NN phase shifts have

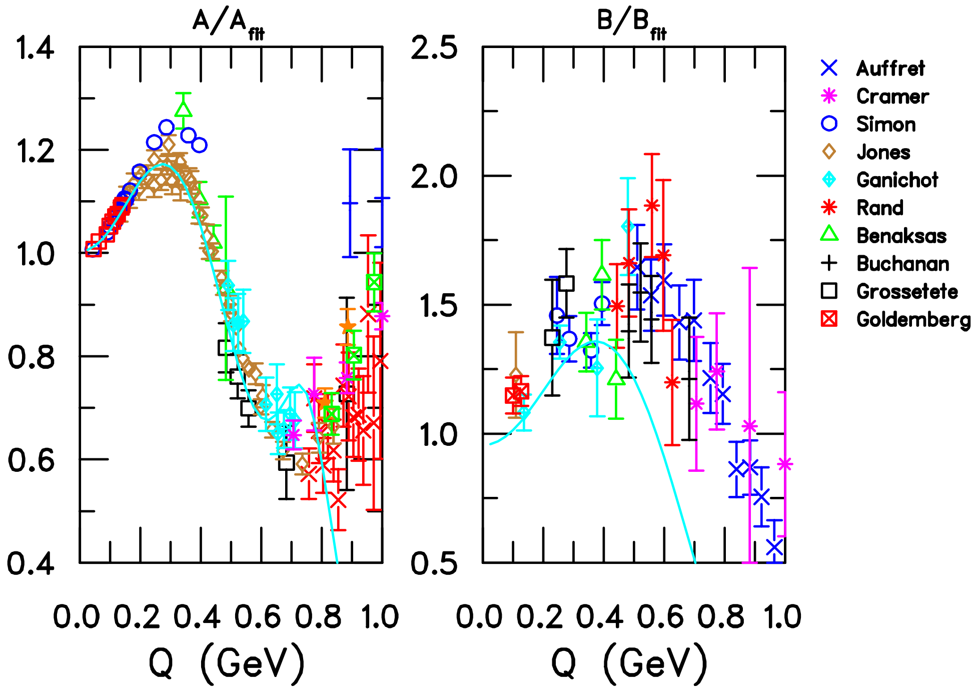

FIGURE 3. χPT calculation of the deuteron A and B structure functions, compared to data. The data and curves were divided by the corresponding A and B fit functions. The first authors of the B references are listed to the right of the figure, see [5–8] for the references.

been fitted, the calculation to this order is essentially parameter free, with only a choice of the nucleon form factor parameterization - the *MMD* parameterization [29] was used - and a question about to what order the calculation must be carried out so that it has converged. Because χPT includes pions, the calculations are applicable up to much higher momentum transfers that are the pionless EFT calculation. Figure 3 shows that precise agreement[2] between χPT and the A data - assuming the Saclay data are correct - is possible up to momentum transfers of perhaps 0.6 GeV. With the B data, which has only 20% or so uncertainties, the agreement is only good up to 0.3 GeV; it is possible that there is more short distance contribution to B and thus the convergence of the theory for B is not as good. However, if the Mainz A data are more nearly correct, it would be necessary to continue the calculation to higher order, which will include terms that have to be determined from the form factor data. Presumably the next order would then improve agreement with both A and B. These recent results represent an improvement on the earlier work of [27]. The recent calculation of [28], which also claims technical improvements upon [27], tends to overpredict G_C and G_M, while underpredicting G_Q.

2 *Conventional nonrelativistic calculations*

A set of conventional nonrelativistic calculations, with *no meson exchange currents* or other corrections, is shown in Fig. 4. In this limit, the deuteron properties depend solely on the wave functions. The calculations (in order of decreasing magnitude at $Q = 0.1$ GeV^2) use W16 (long dot-dashed), CD Bonn (short dashed), AV18 (solid), IIB (short dot-dashed), and Paris (long dashed) wave functions. The W16 and IIB models use the S and D wave functions of a relativistic model, neglecting the P-state components. The variation of these models is only about $\pm 2\%$, and the models are generally higher (lower) than the Saclay (Mainz) data.

The suggestion from pionless EFT of the importance of the asymptotic S state normalization suggests that, in these nonrelativistic calculations, the agreement with either the Mainz or Saclay data might be improved by adjusting the potential to change the size of the asymptotic S state. However, the pionless EFT calculation starts to disagree with the data at lower Q than the region of the Saclay vs. Mainz discrepancy. For a wave function only model, adjusting the potential is the only freedom available, but it is likely to worsen agreement with NN scattering. Other physics is likely important, and we now turn to relativistic models.

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2) One has to worry about the possible logical circularity of the agreement of this and other theories. The MMD fit uses the Saclay extraction of G_{En} from their A data. Insofar as the wave function model and corrections are similar, other calculations should then reproduce the Saclay data. The VOG calculation - see Section II A 3 - for example uses the MMD form factors but agrees better with the Mainz data. See also Section II B.

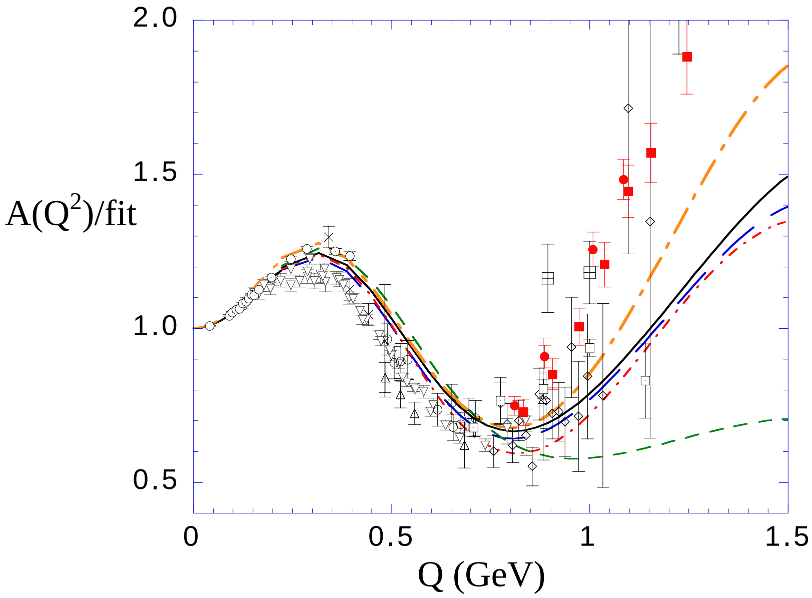

FIGURE 4. The data for A at low and moderate Q, divided by the fit function, compared to five nonrelativistic calculations described in the text.

3 Relativistic and quark model calculations

Figure 5 compares seven relativistic calculations and one quark model calculation to the $A(Q)$ data. All of these calculations were done without the "famous" $\rho\pi\gamma$ meson-exchange current, which is not well understood, and has a negligible effect in the Q regime of this proposal. The calculations include both propagator formulations and Hamiltonian dynamics (instant, point, and front form calculations). The calculations, ordered from largest to smallest at $Q = 0.1$ GeV^2 are:

Van Orden, Devine, and Gross (VOG) [30]: propagator formulation using the relativistic impulse approximation and the Gross equation (left panels, long dashed line)

Forest, Schiavilla and Riska (FSR) [31]: Hamiltonian instant form with no v/c expansion (left panels, solid line)

Arenhövel, Ritz and Wilbois (ARW) [32]: Hamiltonian instant form with a v/c expansion (left panels, short dashed line)

Allen, Klink, and Polyzou (AKP) [33]: Hamiltonian point form (right panels, medium dashed line)

Carbonell and Karmanov (CK) [34]: Hamiltonian front-form with a dynamical light front (right panels, long dashed line)

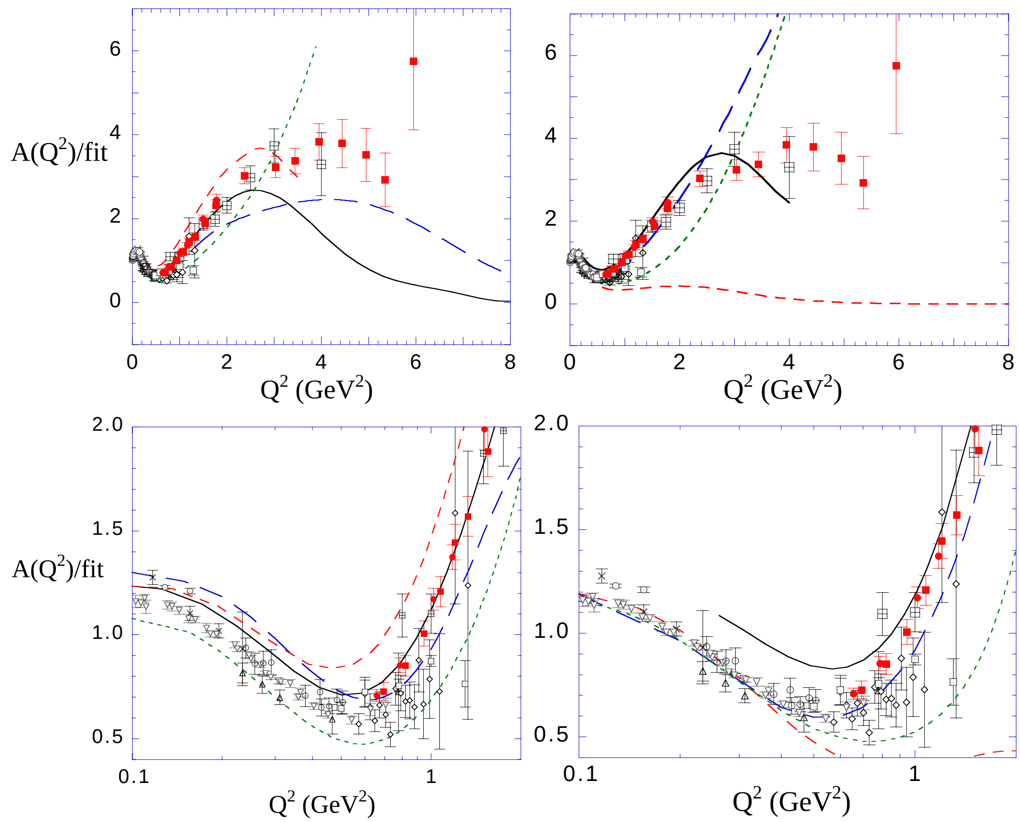

FIGURE 5. The data for $A(Q)$, compared to eight relativistic calculations. Left panels show the propagator and instant-form results: FSR (solid line), VOG in RIA approximation (long dashed line), ARW (medium dashed line), and PWM (short dashed line). Right panels show the front-form CK (long dashed line) and LPS (short dashed line), the point-form AKP (medium dashed line) and the quark model calculation DB (solid line).

Lev, Pace, and Salmé (LPS) [35]: Hamiltonian front-form with a fixed light front (right panels, short dashed line)

Phillips, Wallace, Devine, and Mandelzweig (PWM) [36]: propagator "equal-time" formulation using the Mandelzweig and Wallace equation (left panels, dotted line)

The solid line in the right panels is a nonrelativistic quark compound bag model calculation (DB). While there have been many investigations concerning the implications of pQCD and helicity conservation on the deuteron properties, these limits are clearly not of concern in the momentum range of this proposal.

An examination of Figures 4 and 5 shows that the nonrelativistic calculations tend to be about equal to or smaller than the ARW calculation, but definitely bigger than the CK calculation. The calculations of VOG, FSR, and ARW, which tend to agree better with the Mainz data, are more technically complete than are the calculations of AKP, CK, LPS, and PWM [8] which tend to agree better with the Saclay data. Thus, theoretical bias would suggest the correct trend is the Mainz, rather than the Saclay data. However, the larger amount of Saclay data, as well as the overlap with higher Q experiments from other labs, suggests instead that the correct trend is below the nonrelativistic calculations. It appears then that the relativistic corrections (that is, the net effect of including all physics beyond the nonrelativistic wave function only model) could be either positive or negative, are as much as several percent for the momentum transfers of this proposal, and may not be under control.

Figure 6 explores this issue an another context, using values for the charge form factor extracted from simultaneous fits to the A, B, and t_{20} [5]. The black squares are the G_C data from [5], while the red circles include Coulomb corrections [23]. There are several percent differences between the calculations, and these data are not sufficiently accurate to distinguish between the calculations. However, A is dominated by G_C at least up to $\approx$0.45 GeV, and these data are biased by the numerous Saclay data points to favor lower values of G_C; using only the Mainz data in his region would lead to a 3 - 4% increase in G_C, which would favor the RIA / CIA calculations.

4 Summary: comparison of theory to data

We have shown above that pionless EFT can at present only describe the deuteron well at very low momentum transfers, perhaps up to Q of 0.1 - 0.2 GeV. χPT theory has been shown to give approximate agreement up to several hundred MeV in [27] and [28], and good quantitative agreement in [26] - if the Saclay $A(Q)$ data are correct. If the Mainz data are more correct, it will be necessary to perform a higher order calculation.

The nonrelativistic potential calculations lie between the Saclay and Mainz data sets, and have variations of 1 - 2%. If the Saclay $A(Q)$ data at low Q are correct,

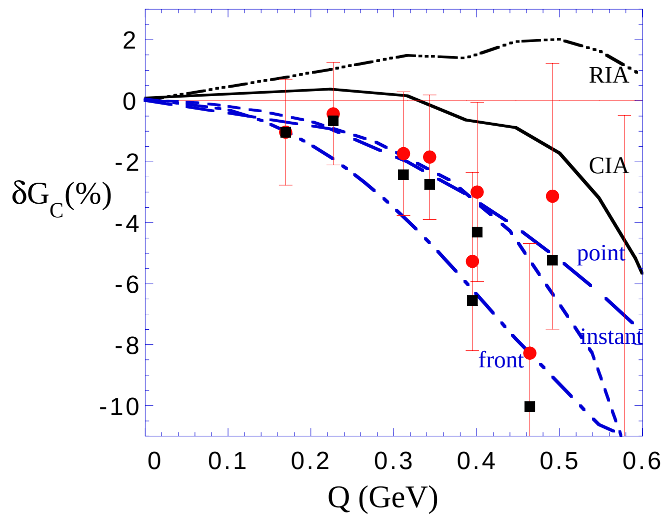

FIGURE 6. Experimental data for G_C compared to five relativistic calculations, relativistic impulse approximation (RIA) and full calculation (CIA) from VOG, and point, instant, and front forms from AKP, ARW, and LPS, respectively. All data and curves are shown relative to the nonrelativistic AV18 potential calculation.

the AKP, CK, and LPS calculations are in very good agreement with the data. If however the Mainz data are correct, the FSR and VOG calculations appear to be most correct. If one examines the $B(Q)$ structure function - see Figure 1 - in particular in the region near the minimum, $Q \approx 2$ GeV^2, the VOG, LPS, DB, and FSR calculations are closest to the data. If one examines instead t_{20} - see Figure 1 - the LPS calculation is by far the least satisfactory. One might argue AKP and DB are also somewhat too negative after the minimum, but the other calculations are all more or less reasonable.

Thus, if the Mainz data are correct, both the VOG and FSR calculations provide a reasonable good account of the full data set. However, if the Saclay data are correct, it appears that *no* conventional calculation is entirely satisfactory.

As indicated above, our theoretical bias is that the VOG and FSR calculations are more complete and mature than the others. Thus it will be more difficult to improve these calculations if they are found to be in disagreement with the data. Perhaps the main point to take from this discussion is that there is a strong effort by many different theoretical groups to understand the deuteron structure. High precision data in the region of the discrepancy between the existing Mainz and Saclay data sets would be of great interest.

B Extraction of G_{En}

One of the major aims, and highlights, of the Saclay experiment was the extraction of G_{En} from the elastic scattering data. In a nonrelativistic, purely wave function model for the deuteron, the deuteron elastic form factors arise from a product of deuteron body form factors multiplied by isoscalar nucleon form factors, e.g., $G_{Ep} + G_{En}$. (The expressions can be found in any of the recent reviews as well as a number of articles.) Thus, knowledge of the deuteron charge form factor and the proton electric form factors allows a direct calculation of G_{En}. In the range of the Mainz data G_{Ep} is close to unity, and well known, while G_{En} is perhaps 0.05. With $A \propto G_C^2$, 5 - 10% changes in A lead to 0.025 or 0.05 changes to G_{En}.

Recent polarization experiments have provided a small number of precise data points, which generally imply that G_{En} is slightly larger than in the Saclay analysis, 0.05 - 0.06 rather than the 0.04 of the Saclay analysis. However, it should be clear from the description above that the analysis is model dependent; corrections must be made for various meson-exchange current and relativistic effects, as well as Coulomb distortions. The 2% variations of the nonrelativistic theories imply that it is very difficult to extract G_{En} with good precision. It is clear that a modern theoretical reanalysis of the Saclay data along with all the recent polarization data would be desirable [37], and that uncertainties on the cross section directly impact the extraction of G_{En}. Since the polarization experiments are so difficult, it is desirable to provide a firmer basis for the elastic scattering G_{En} extraction.

C Evaluation of low Q experiments

In this section, we describe in greater detail the three high precision data sets for the deuteron A structure function at low Q.

The Monterey experiment [11] (red open squares in Figure 2) measured a ratio of elastic *ed* to *ep* scattering using cooled gas targets and electron energies up to 105 MeV. Thirty-three ratios were used to determine the deuteron $A(Q)$ structure function, and thus G_C, for nine different Q points - for these very low Q points, G_C accounts for ≈99% of the cross section. The claimed relative systematic uncertainty of the deuteron to hydrogen cross section ratio was ≈0.3%.

The Mainz experiment [9] (blue open circles in Figure 2) used liquid and gas targets to determine elastic cross sections at 8 beam energies, from 80 to 298.9 MeV, with laboratory electron angles from 30° to 157°. The claimed deuteron cross section systematic uncertainty was ≈0.7%, with the normalization checked with hydrogen data. For the smaller Q Mainz data, $B(Q)$ is too small to be measured, and corrections were calculated. For the four highest Q points, the points for which there is the prominant disagreement with the Saclay data, $B(Q)$ was determined by a Rosenbluth separation.

Figure 7 shows $\frac{d\sigma}{d\Omega}/\epsilon\frac{d\sigma}{d\Omega}|_{NS} = \Big[A(Q) + B(Q)\tan^2(\theta/2)\Big]/\epsilon$ as a function of ϵ for

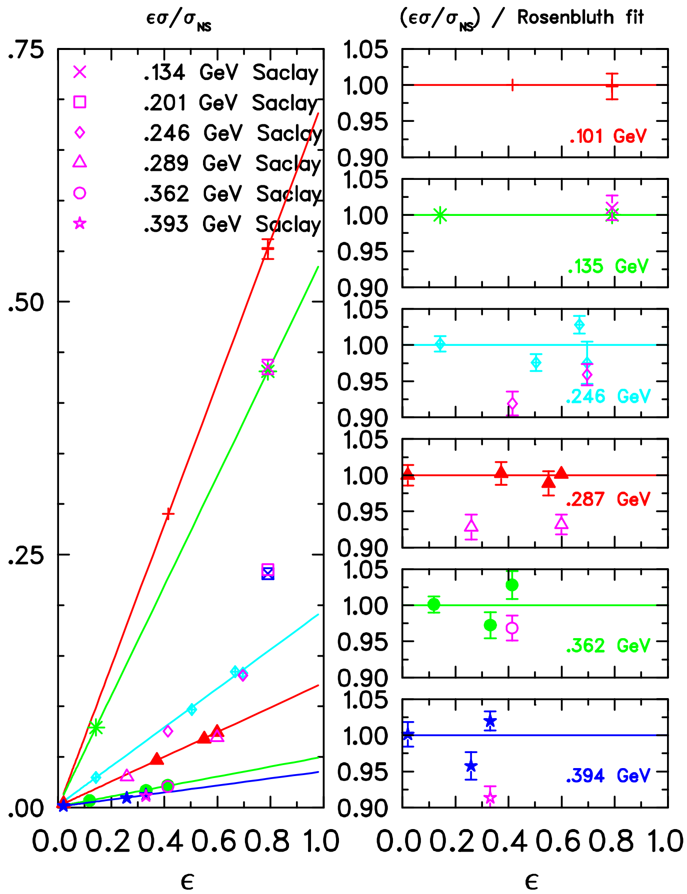

FIGURE 7. The left panel shows Rosenbluth separations for the Mainz data. Saclay data at essentially the same Q are given by the corresponding open symbols. (The 0.20 GeV data are shown as an additional check of the overlap of Saclay and Mainz cross sections; there are insufficient data for a separation.) The right panel shows the data in detail using the ratio of the data points to the Rosenbluth separation, so that the consistency of the points can better be seen. Some of the variation arises from the points being at slightly different Q values.

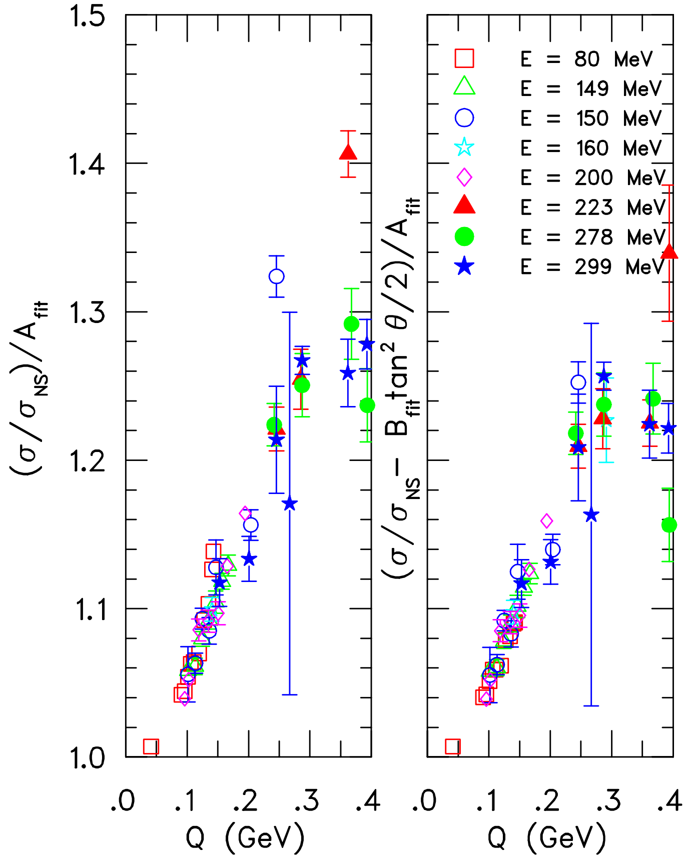

FIGURE 8. The Mainz reduced cross sections, at low Q. The data in the left panel are divided by the fit function for $A(Q)$, which, by not including an angle correction, should leave lower energy data systematically higher than the higher energy data. The data in the right panel have an estimate of the $B(Q)\tan^2(\theta/2)$ contribution subtracted before being divided by the $A(Q)$ fit function. The subtraction should roughly bring all data sets into alignment.

these data[3], as well as for some of the Saclay data. The Rosenbluth fits are also shown[4]. It is apparent that at most of the Q values the spread in the forward angle, high ϵ, points is larger than desirable. Most of the spread is related to the points not being exactly at the same Q. The most forward angle, high energy, large ϵ points were taken at 298.9 MeV beam energy, and scattering angles of 50°, 60°, 80°, and 90°. The contribution of $B(Q)$ to the cross section ranges from about 0.5% to 5% for the forward angle points at each of these Q.

We further examine the self-consistency of the Mainz data by comparing reduced cross sections in Figure 8. Here it can be seen that there are more or less normal

[3] The Mainz publication [9] only did separations for the four higher Q values shown; uncertainties on B were too large to be meaningful at the lower Q values.
[4] The fits are not constrained to be 0 at $\epsilon = 0$; B is small.

statistical fluctuations in the data, and that an approximate correction for the B contribution brings the data into better alignment; two of the backward angle higher Q points that are off scale in the left panel come into reasonable agreement in the right panel. [5]

The Saclay data [10] (brown open diamonds in Figure 2) used 4 energies from 200 to 650 MeV, with scattering angles from 35° to 100°. Careful attention was paid to systematic effects including detection efficiencies and solid angles. The contribution of $B(Q)$ to the cross section was calculated, based on previous measurements, and subtracted. The claimed systematic uncertainties were 1 - 1.5%. The disagreement with the Mainz measurements comes most directly from four 300 MeV data points, for which the reduced cross sections ($\frac{d\sigma}{d\Omega}/\frac{d\sigma}{d\Omega}|_{NS}$) disagree with those of the 298.9 MeV Mainz data *at the same scattering angles* by about 10% - see Figure 7. (The difference in Q and σ_{NS} for the 1 MeV change in energy leads to only a ≈1% correction.) It can be seen in Figure 7 that the Saclay data are slightly lower than the corresponding Mainz data, and further, for Q = 0.248 GeV, the Saclay data even indicate $B(Q) \approx 0$, since it is required to be nonnegative. The Saclay article mentions, without explaining, the disagreement with Mainz.

We examine the Saclay reduced cross sections more closely in Figure 9. In the left panel we have divided by the fit function for $A(Q)$ only, to remove much of momentum dependence *without* introducing any angle dependence related to the $B(Q)$ correction. In the right panel, an approximate correction is made for the $B(Q)$ contribution. The main point is that the lower beam energy data should be equal to, or slightly above, the higher beam energy data, due to the larger contribution from $B(Q)$ at the larger scattering angle, but the lower Q Saclay data are *inconsistent* with this principle. The 200 MeV data (stars) are *systematically less* than the 300 MeV data (circles), and the 300 MeV data (circles) are *less* than the first few 500 MeV data points (triangles). [6] For points below Q = 0.3 GeV, the 200 MeV data are systematically 2% below the 300 MeV data. Thus, it is reasonable to question whether there is a normalization problem in the Saclay data, particularly for the low energy data sets, which might affect theoretical interpretation.

To summarize, while the overlap of the lower Q Mainz data looks good, the higher Q data for which the Rosenbluth separations were performed shows more variation than is desirable. The overlap of the Platchov data from different energies indicates systematic deviations can be seen up to $Q \approx 0.35$ GeV. Thus, it appears that the underlying source of the variations in the low Q Saclay $A(Q)$ values shown in Figure 2 is a systematic energy to energy variation, rather than a random point to

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5) In the published Mainz data table, there are four kinematic points for which the quoted cross section is inconsistent with the quoted reduced cross section. For three of the points the difference is exactly a factor of 10, while for the fourth point the difference is a factor of 12.5. In each case, we have used the published reduced cross section value. The large, ≈10% uncertainty, on the Q = 0.27 GeV point is as published.

6) Note that for a high precision comparison, it is also necessary to study Coulomb corrections, as was done by Sick and Trautmann [23]. This correction appears to be a few tenths of one percent, in the overlap of the Saclay data at the different energies.

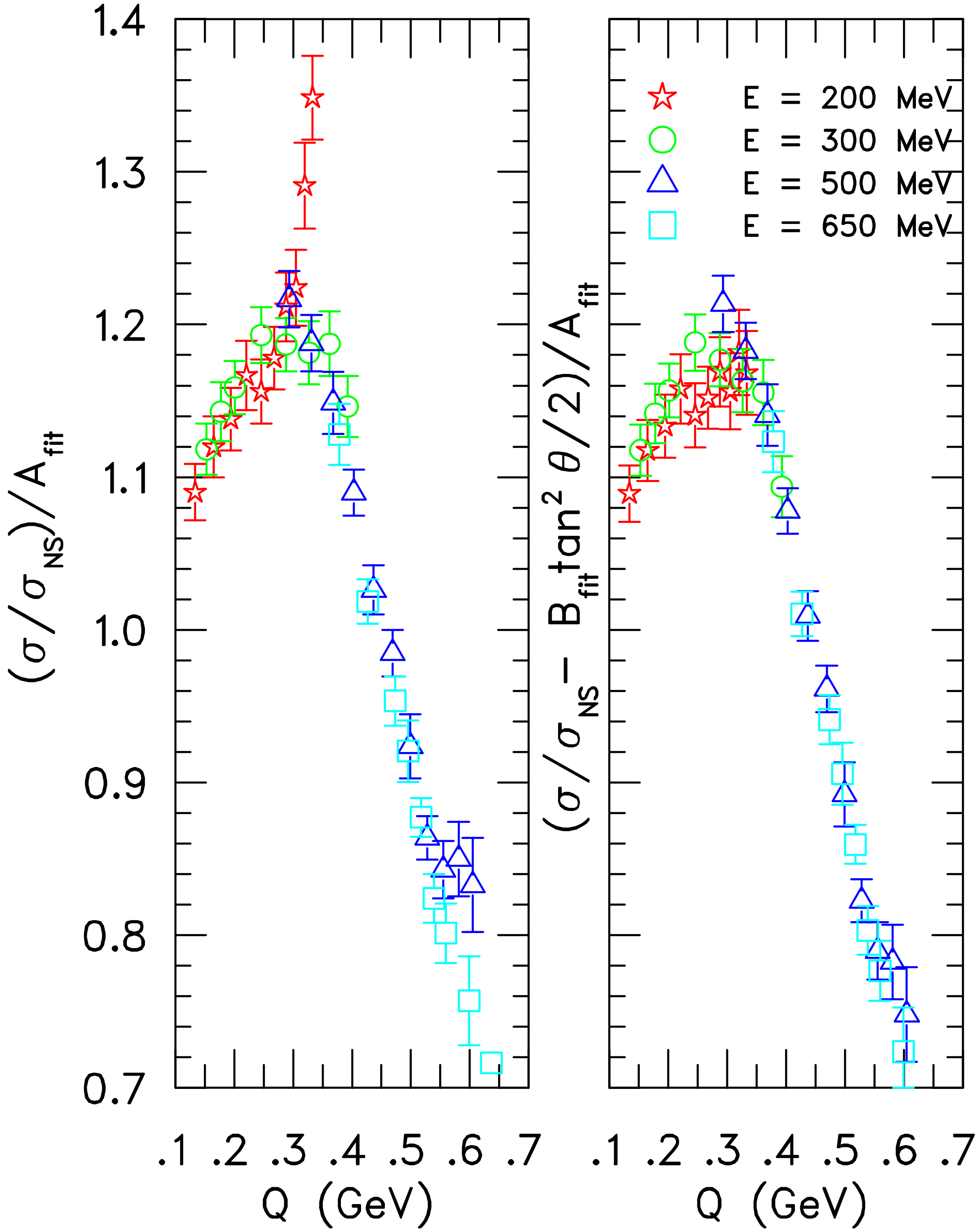

FIGURE 9. The Saclay reduced cross sections, at low Q. The data in the left panel are divided by the fit function for $A(Q)$, which should leave lower energy data systematically higher than the higher energy data. The data in the right panel should be roughly aligned.

point variation. Given the overall uncertainties, probably neither of these problems would be taken by themselves to indicate definite problems in the data. It is only in the context of the disagreement of the two experiments that if becomes clear that something is wrong.

III PROPOSED MEASUREMENTS

The goal of this experiment is to resolve the discrepancy between the Mainz and Saclay data sets by measuring precise and accurate cross sections. We will do this primarily by determining the absolute *ed* elastic cross section to <1% statistically and to 2 - 3% systematically in the region of $0.2 < Q < 0.8$ GeV/c. To ensure that these data are sufficient and well calibrated, we will also determine even more precisely the *ed* to *ep* cross section ratio for each point, as well as the Q dependence of the *ed* cross sections, which allows determination of a precise $A_{relative}(Q)$. We will make each measurement with both Hall A spectrometers to provide an additional cross check. As a final cross check, we will repeat half of the data points at a second beam energy. Because these measurements are performed at "high energy", relative to previous experiments, the contributions of $B(Q)$ are small, $\leq$1% for all but our highest momentum transfer setting. The issues instead are keeping systematic uncertainties under control, keeping count rates from being too large, and being able to prove that the data are self consistent and accurate. Having a measurement at a second energy, for which $d\sigma/d\Omega|_{NS}$ is different, is an important step in demonstrating that we have correctly evaluated the systematic uncertainties.

A Absolute cross section measurements

The cross section is directly determined from the measured counts through

$$\frac{d\sigma}{d\Omega} = \frac{Counts}{L_t \cdot \rho_t \cdot \frac{Q_b}{e} \cdot \Delta\Omega \cdot R \cdot \Pi_i \epsilon_i} \tag{4}$$

Where L_t is the target length and density, ρ_t is the target density in atoms/cm^3, Q_b is the beam charge and e is the charge carried by electron, R is the radiative correction factor, and $\Pi_i \epsilon_i$ is the product of efficiencies, which includes the efficiencies of and dead time corrections for the detectors, the trigger, the DAQ, and track reconstruction. Experiments that have paid careful attention to systematics in Hall A have been able to determine absolute cross sections to about 2%, in particular during optics studies using elastic scattering at moderate currents on a thin ^{12}C target of precisely known thickness. In addition to the uncertainties on these factors, one must know how backgrounds affect the yield and the Q value at which the data are taken.

TABLE 2. Estimated cross section change (in percent) for changes in kinematic parameters, for $E = 0.857$ GeV and the Q points we propose to measure. Also shown is the estimated contribution from the $B(Q)$ structure function to the cross section in %. For the same Q points, the cross section changes increase with beam energy, while the $B(Q)$ contribution decreases with beam energy. The size of the systematic changes given are the 1σ estimates for these parameters in Hall A.

Q (GeV)	δ_E of 0.02%	$\delta_{E'}$ of 0.04%	δ_θ of 0.6 mr	Total	$B(Q)$
0.20	0.08	0.00	1.55	1.56	0.02
0.25	0.09	0.02	1.37	1.37	0.04
0.30	0.09	0.03	1.23	1.24	0.08
0.35	0.10	0.04	1.12	1.13	0.15
0.40	0.10	0.05	1.03	1.04	0.25
0.45	0.11	0.06	0.95	0.96	0.40
0.50	0.11	0.06	0.88	0.89	0.60
0.60	0.12	0.08	0.77	0.78	1.22
0.70	0.13	0.09	0.67	0.69	2.21
0.80	0.13	0.11	0.59	0.61	3.81

1 Detectors and backgrounds

The scattered electrons will be detected in the HRS spectrometers with their standard detector packages, which consist of trigger scintillators, VDC chambers, gas Cerenkov detectors and double-layer shower counters. Elastic scattering measurements are relatively clean, due to the lack of higher energy particles scattering from the magnet pole faces. The PID detectors are used to remove small π^- background. A coincidence of scintillators S1 and S2 provides the standard trigger, and efficiencies are checked with a trigger that has a reduced scintillator hit requirement, but also requires the gas Cerenkov or an additional trigger scintillator, S0, to fire.

In addition to the deuteron events, there will be events coming from the target cell walls; these wll be subtracted by an empty target measurement. The experimental resolution is limited primarily by multiple scattering and the determination of scattering angle, but it is sufficient to cleanly separate the *ed* elastic peak from threshold electrodisintegration in all kinematics.

2 Determination of Q

Since $A(Q)$ is a steep function of Q, it is important to know the kinematics of the measurements well. Table 2 shows the sensitivity of the cross sections to the beam and scattered electron energies, and to the scattering angle. For this calculation, these quantities were treated as independent, though they are constrained by $Q^2 = 2m_d(E - E')$.

The beam energy will be determined by ARC and EP measurements; once these absolute energy measurements have been done, the relative energy can be reliably determined from magnet settings and beam position monitors. To ensure the energy is stable, the accelerator feedback locks should be set for Hall A during this experiment.

The spectrometer constant is known well enough to determine the outgoing energy to 0.04%, and will be checked at each setting with $^{12}C(e, e')$. (Of course, it is the energy at the vertex that is important, and energy loss corrections are minimized with a short, narrow target.)

The largest systematic is related to the determination of the absolute scattering angle. Two sets of beam position monitors upstream of the scattering chamber will provide information on beam incident angle (to 0.1 mr) and beam position. The spectrometer pointing is determined by multiple systems; improved monitoring is being developed for the G_{Ep} cross section experiment, E00-001. The pointing, as well as the solid angle and y_{target} calibration, will be checked with $^{12}C(e, e')$ data at each angle.

The large uncertainty of 0.6 mr comes from the uncertainty in the position of the sieve slit relative to the spectrometer, which ends up dominating the uncertainty in Q. Studies are currently being done of, e.g., $p(e, e'p)$ and other coincidence reactions to see if the offset angle between the sieve slit and spectrometer is constant and can be precisely determined. It is estimated that these studies will reduce the uncertainty in the absolute angle to 0.1 - 0.2 mr, thus reducing the overall systematic uncertainty in our Q determination to be always better than 0.5%. In this case, we would need 1 shift of beamtime to do a set of three coincidence $(e, e'p)$ measurements to verify the angle calibration for this experiment. Discussions are also underway [38] concerning construction of a precise angle measurement system, using a precision table including beam position monitors, a microstrip detector, and a thin wire target. Scattered particles passing through the microstrip detector into the spectrometer would allow precise determination of the spectrometer angle.

3 Beam charge

Knowing the integrated charge for absolute measurements is one of the most difficult issues. (Of course, only the relative charge is needed for angle dependences and for the deuterium to hydrogen ratios.) The general system in Hall A is to determine the charge in the Hall with BCMs which are calibrated to an Unser monitor. Operational experience in Hall A is that current calibrations, are good for higher currents to ≈1%, and, once performed, are stable at the 1% level for months. The two BCMs are each read out with three V to F converters; ths variaton of these plus the Unser monitor, allows cross checks at the <<1% level. The systems have not been as extensively studied for currents below about 3 μA; as we are operating at lower currents for part of the experiment, we will need to carefully perform calibrations. We will require several hours of facility development time to calibrate and study the calibration, and its time variation, at low currents. Hall A currently has plans and funds to develop a "silver calorimeter" to determine the current, at low currents, to <<1%; this new device may be needed for precise absolute measurements for our lowest Q points. Thus, we estimate the current will be known to 1% absolutely, but to 0.1% relatively.

4 Cryotarget

The standard 4 cm Hall A cryotarget cells are sufficient for this proposal. For these cells, the cryotarget length and density can each be determined to ≈0.15%, leading to a 0.2% uncertainty in its areal density. Boiling is not an issue at low currents, and the use of a monitoring spectrometer will allow it to be measured precisely, to ≈0.1%, for our highest current runs. The relative density between the H and D targets is known to 0.3%.

However, the standard cryotarget cells are not optimal for this experiment. Shorter, narrower cells would reduce radiative corrections, energy loss corrections, the count rate for small Q points, multiple scattering (improving resolution and systematics) and the angle dependence of the solid angle. Statistical uncertainties (for constant beam time) would increase from the larger relative count rate of background from the cell walls to deuterium, and slightly poorer statistics at larger Q, while systematic uncertainties may increase from uncertainties in the average length of the target, for the rastered beam - a narrower target will probably have smaller radii of curvature on the entrance and exit windows. The use of Havar in a small diameter vertical flow cylindrical cell, as proposed in approved experiment E01-104, would be an improvement. To be able to optimize the target configuration, we will request a few hours of facility development time to determine the ratio of deuterium to aluminum rates in our kinematics. This information along with detailed systematics studies will allow the target configuration to be optimized.

Two loops filled with liquid hydrogen and deuterium are needed as well as a dummy target for background measurements. In addition, a set of five carbon foils (25 mg/cm^2 each) will be mounted on the target ladder. They will be uniformly spaced within a 4.0 cm distance along the beam directions, and will be used in optics calibration runs and in elastic carbon runs. Since the experiment will be running with very low currents (except for Kin-9_d and Kin-10_d), target density fluctuations caused by beam heating is negligible. The target density will be determined through temperature and pressure measurements.

5 Solid angle

Experiments in Hall A with thin targets have determined the solid angle to ≈1%, and absolute cross sections to 2 - 3%. For this proposal, we assume the standard Hall A 4-cm "beer can" cell, we will be operating with a *slightly* extended target, with $\Delta y_{target} = \pm$ 0.5 – 1.8 cm. The absolute solid angle will be determined by using the multiple carbon foil target, to nearly 1%. The solid angle for the ratio measurements of D to H is essentially identical, since we measure at the same spectrometer angle with the peak centered at the same point in the focal plane for all measurements.

6 Radiative corrections

Radiative corrections for the hydrogen and deuterium are essentially identical, and cancel in the relative cross sections, but for the absolute cross sections they are about 40%, varying by ±5% across our angle range. The uncertainty in R will be about 1% absolute, and much smaller in the relative measurements.

7 Efficiencies

Care must be taken with the forward angle data, for which the raw count rate will be ≈100 kHz. By taking prescaled data with two independent, but commonly gated, data acquisition systems, as was done for the g_2^n experiment, E97-108, during summer 2001, it will be possible to have small DAQ dead times which can be precisely corrected. Scintillator and trigger dead times are also small. Scintillator efficiencies are monitored by having a tight trigger, which requires all four phototubes on scintillator paddles in S1 and S2 to fire, as well as a loose trigger that is used to study the inefficiency. Having the two independent DAQs limits the number of trigger types and the uncertainty in the dead time corrections. The largest difficulty is multiple tracks in the VDCs, which lead to an uncertainty in the tracking efficiency at high rates. The VDCs have a maximum drift time of about 0.25 μs. At 100 kHz rate, there is a $0.25\mu s/10\mu s = 2.5\%$ probability of a second event leading to signals seen in the drift chamber. Most of these events will not cause problems as they will be spatially separated from the triggering event, and, depending on the relative timing, either the long or short drift times will be eliminated from the event analysis. The exact level of the uncertainty depends on the quality of the tracking algorithyms, and the ability to recognize and remove poorly tracked events from the data without biasing it - one has to distinguish between events that really should not have a track and events for which the tracking did not produce a good track.

B Hydrogen ratio measurements

As indicated above, the deuteron elastic form factor $A(Q)$ will be extracted directly from the cross sections to better than $\pm 3\%$ accuracy. Absolute ep elastic cross sections will also be determined at each point, to check our experimental procedures and to allow the deuteron $A(Q)$ form factor to be extracted relative to the proton form factors, from the ratio of the elastic ed to ep yield.

For elastic ep scattering, we have:

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \sigma_{Mott} \frac{E'_{ep}}{E} \left[\frac{G_E^2(Q_{ep}) + \tau G_M^2(Q_{ep})}{1+\tau} + 2\tau G_M^2(Q_{ep}) \tan^2\left(\frac{\theta}{2}\right)\right], \qquad (5)$$
$$\equiv \sigma_{Mott} \frac{E'_{ep}}{E} S_p(Q_{ep}, \theta)$$

At each kinematics, the central momentum of the spectrometer will be slightly adjusted such that ep and ed elastic peak fall at essentially the same location on the focal plane - the cancellation will not be exact since $dp/d\theta$ depends on the target and scattering angle θ. This arrangement will ensure that in each setting there will be the same solid angle for the hydrogen and deuterium data. Furthermore, ratio measurements will be insensitive to any position dependence of the detector efficiency.

Under the same target cuts and within the same scattering angle bin, the ratio of the charge-normalized yield is:

$$\frac{Y_{ed}(Q_{ed}, \theta)}{Y_{ep}(Q_{ep}, \theta)} = \frac{1 + \frac{2E}{m_p} \sin^2\left(\frac{\theta}{2}\right)}{1 + \frac{2E}{m_d} \sin^2\left(\frac{\theta}{2}\right)} \cdot \frac{S_d(Q_{ed}, \theta)}{S_p(Q_{ep}, \theta)} \cdot \frac{\rho_D}{\rho_H} \cdot \frac{R_{ed}}{R_{ep}} \qquad (6)$$

where R_{ed} and R_{ep} are the radiative correction factors associated with the ed and the ep measurements. The relative charge can be determined to $\approx$0.1%. The relative yields will be determined to about 0.2% statistically. The target densities for H and D are each known to about 0.2%, and the uncertainty in the relative density is about 0.3%. Uncertainty in the relative radiative corrections will be of order 0.1%. Uncertainties in corrections for the slight differences in kinematic factors - because the data point central and average values are different - are very small, as are uncertainties in the relative efficiencies between H and D, which were omitted from the equation. Thus, the relative cross sections measurements will be better than <1%.

C Deuteron ratio measurements

As a further check on the systematics of the data, we will also measure relative deuteron cross sections, and repeat all measurements with each of the spectrometers. For the relative measurements, one spectrometer measures the relative

TABLE 3. Table of kinematics and count rates, for $E = 0.857$ GeV.

	θ (degree)	Target	E' (GeV/c)	Q (GeV/c)	I_{beam} (μA)	Rate (Hz)	Time (Hours)
Kin-1_d	13.50	LD_2	0.8463	0.200	1.0	70k	0.50
Kin-1_p		LH_2	0.8359	0.199	1.0	180k	0.25
Kin-2_d	16.95	LD_2	0.8403	0.250	1.0	16k	0.50
Kin-2_p		LH_2	0.8243	0.248	1.0	67k	0.25
Kin-3_d	20.50	LD_2	0.8329	0.300	1.0	4k	0.50
Kin-3_p		LH_2	0.8101	0.297	1.0	28k	0.25
Kin-4_d	24.05	LD_2	0.8243	0.350	1.0	1.3k	0.50
Kin-4_p		LH_2	0.7940	0.344	1.0	13k	0.25
Kin-5_d	27.75	LD_2	0.8142	0.401	3.0	1.2k	0.50
Kin-5_p		LH_2	0.7755	0.391	1.0	6.6k	0.25
Kin-6_d	31.50	LD_2	0.8029	0.450	10.0	1.4k	0.50
Kin-6_p		LH_2	0.7553	0.437	1.0	3.5k	0.25
Kin-7_d	35.40	LD_2	0.7902	0.500	10.0	500	1.00
Kin-7_p		LH_2	0.7332	0.482	1.0	1.9k	0.25
Kin-8_d	43.65	LD_2	0.7609	0.600	50.0	350	1.50
Kin-8_p		LH_2	0.6842	0.569	1.0	600	0.75
Kin-9_d	52.70	LD_2	0.7263	0.700	50.0	61	3.0
Kin-9_p		LH_2	0.6302	0.652	1.0	200	1.0
Kin-10_d	62.90	LD_2	0.6863	0.800	50.0	11	4.0
Kin-10_p		LH_2	0.5724	0.731	1.0	85	1.0
Total beam on target: 2×17 **hours**							**34**

luminosity at one of the kinematics points, checking at the 0.1% level, while the other spectrometer measures the deuterium (and hydrogen and carbon) absolute cross sections at all of the angles. The dominant angle dependent uncertainty is from the determination of Q (1.4%)[7]; other relative uncertainties include statistics (0.2%) solid angle (0.5%), and radiative corrections (0.2%).

D Run plan and kinematics

We plan to start the experiment with a set of systematic and calibration checks, including beam energy measurements and current calibrations. Boiling tests will be done during one of the actual kinematic points. Recall also that we are planning on some calibration studies during facility development time prior to the experiment.

The kinematics and count rate estimate are listed in Table 3, for a beam energy of $E = 0.857$ GeV. (This is a typical one-pass beam energy; the exact energy is not critical. If the energy is too high, it will be necessary to increase the momentum

[7] The angle offset is probably constant to much better than the 0.6 mr 1σ uncertainty level, which was used in estimating the 1.4% uncertainty.

transfer of the lowest Q point.) The Table indicates that high data rates are possible; indeed, the difficulty is avoiding too high a data rate. The experimental time is largely spent in overhead switching between settings, and performing calibration measurements.

The run plan is to fix HRS-left at Kin-4 as a luminosity monitor, while HRS-right performs all measurements from Kin-1 to Kin-10. Thus, the deuteron form factors relative to those at Kin-4 may be precisely determined. Then, the roles of the spectrometers will be reversed, and all measurements will be repeated. For each angle setting - and thus multiple times for Kin-4, we will measure spectra at three momentum settings, one for $^{12}C(e,e')$ elastic, one for $^{2}H(e,e')$ elastic and empty cell, and one for $^{1}H(e,e')$ elastic, empty cell, and $^{12}C(e,e')$ quasifree scattering. (At forward angles, the differences between E'_C and E'_D are small enough that only one setting will be used.) The ^{12}C data check systematics, while the empty cell data check backgrounds.

As indicated above, this run plan gives us several redundant ways to determine of $A(Q)$. First, the absolute cross sections of ep and ed are independently determined at each angle. Second, the yield ratio of Y_{ed}/Y_{ep} is determined at each setting. Third, the value of $A(Q)$ is determined relative to the $Q = 0.35$ GeV point. Finally, measurements are repeated with two different spectrometers, providing very stringent self-consistency constraints on the measurement results such that the systematic uncertainties can be better understood.

In addition to performing these measurements at a standard one pass beam energy, we are requesting to repeat the measurement of half of the data points at a lower beam energy of 600 MeV. Obtaining consistent values of $A(Q)$ at two energies will add great confidence to the data.

Systematic uncertainties discussed in the sections above are summarized in Table 4. These are uncertainties that can be obtained in a carefully run experiment at present. We have outlined above work on the charge and angle determinations that can substantially reduce these (large) systematics. We have also indicated work to be performed to optimize the target configuration, which involves a tradeoff between various statistical and systematic uncertainties.

IV BEAM TIME REQUEST

The time request is summaized in Table 5. We request 3 days of beam time at an energy near 850 MeV, and 2 days of beam time at an energy of about 600 MeV, for this experiment. This include overhead time of target changes, magnets and spectrometer angle changes, beam energy measurement, beam charge calibration and a spectrometer optics check. Empty cell runs of 10 minutes at each setting are also included. The lower beam energy is the lowest at which it is currently considered standard to run beam to multiple halls.

TABLE 4. Estimated systematic uncertainties on absolute cross sections, hydrogen to deuterium ratio, and $A(Q)$ from the relative *ed* cross section angular distribution. A dash indicates the uncertainty is either negligible or not present.

systematic	uncertainty	$\frac{\delta\sigma_d}{\sigma_{d\ abs}}$	$\frac{\delta(Y_{ed}/Y_{ep})}{Y_{ed}/Y_{ep}}$	$\frac{\delta A(Q)}{A(Q)}$
Beam energy	0.02 %	0.1 %	-	-
Scattered electron energy	0.04 %	0.1 %	-	-
Scattered electron angle	0.6 mr	1.0 %	0.1 %	1.4 %
Beam charge Q	1.0 %	1.0 %	0.1 %	0.1 %
Target areal density	0.2 %	0.2 %	0.3 %	0.1 %
Target boiling	0.1 %	0.1 %	0.1 %	0.1 %
Solid angle $\Delta\Omega$	1.0 %	1.0 %	0.1 %	0.5 %
Radiative correction	1.0 %	1.0 %	0.1 %	0.1 %
$\epsilon_{detector}$	0.5 %	0.5 %	0.1 %	0.1 %
$\epsilon_{trigger}$	0.1 %	0.1 %	-	-
ϵ_{DAQ}	0.1 %	0.1 %	-	-
$\epsilon_{reconstruction}$	0.5 %	0.5 %	0.2 %	0.5 %
Total		2.1 %	0.4 %	1.6 %

V CONCLUSIONS

We request five days to measure the *ed* elastic scattering $A(Q)$ structure function at low Q. The measurements will resolve a $\approx$8% discrepancy between the high (<2%) precision Mainz and Saclay data sets for Q about 0.2 - 0.4 GeV; it appears that there are internal inconsistencies in the lower energy Saclay data, while the overlapping higher Q Mainz data are also not as consistent as one would desire. At these Q, a description of $A(Q)$ is just out of the reach of current NNLO pionless effective field theories, but quite possible using chiral perturbation theory. Furthermore, conventional nonrelativistic theories give roughly the average of the two data sets, while relativistic theories tend to agree either with the Mainz or with the Saclay data. Thus, the new measurements will better test the application of χPT to the deuteron, and will help improve understanding relativistic corrections at low Q. The measurements have potentially high impact on our understanding of the deuteron, yet require minimal beam time, and can be easily done, with a careful experiment in Hall A.

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TABLE 5. Summary of beam time request.

Items	Time (hr) $E_e = 0.85$ GeV	Time (hr) $E_e = 0.60$ GeV
Beam on cryo-targets	34.0	17.0
Beam on empty-target	8.0	4.0
Target movements	8.0	4.0
Spectrometer magnet and angle changes	8.0	4.0
Two accesses to move spectrometer	2.0	-
Beam energy measurements (ARC+EP)	3.0	3.0
Beam charge calibration	2.0	-
Spectrometer optics check	4.0	2.0
$^{12}C(e,e')$ elastic runs	3.0	1.5
Total	**72.0**	**35.5**

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